Geographic Diversification and Coordinated Dispatch for Firm Solar Power in India

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Abstract

This study examines whether geographically distributed solar-plus-storage plants can provide reliable baseload power in India. We simulate 120 solar plants (6 GW solar + 16 GWh battery each) distributed across 18 states, targeting 100 GW aggregate output with a 20% reserve margin. Using hourly capacity factor data from NREL, we compare two dispatch strategies: independent (greedy) operation and centrally coordinated (optimized) dispatch. Our key finding challenges conventional wisdom: **coordination matters more than diversification**. While geographic diversity alone achieves 80% hourly reliability, coordinated battery management achieves 96%-a 16 percentage point improvement from operational strategy alone, not additional infrastructure. This suggests that investment in forecasting and dispatch coordination may yield greater reliability gains than building additional plants.

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1. Introduction

1.1 The Challenge of Firm Renewable Power

India's electricity sector faces a fundamental tension: the imperative to decarbonize while maintaining grid reliability. Solar power, while abundant and increasingly cost-competitive, is inherently variable-unavailable at night and reduced during monsoon season. The traditional solution has been to pair renewables with fossil fuel backup, but this approach limits decarbonization potential.

An alternative approach is to combine solar generation with battery storage at scale, creating "firm" renewable power plants that can deliver consistent output regardless of instantaneous solar availability. However, a single solar-plus-storage plant cannot guarantee 24/7 output-extended cloudy periods will eventually deplete any reasonably-sized battery.

1.2 The Geographic Diversification Hypothesis

The core hypothesis of this research is that **geographic diversification can achieve what a single plant cannot**. Weather patterns are not perfectly correlated across India's vast geography. When Gujarat experiences monsoon clouds, Tamil Nadu may have clear skies. By distributing plants across multiple states, the aggregate output may achieve reliability levels impossible for any individual plant.

This principle mirrors the reliability engineering of conventional power systems: individual coal plants have approximately 85% availability due to maintenance and unplanned outages, yet fleet-wide availability exceeds 99% because outages are uncorrelated. We investigate whether the same principle applies to weather-driven variability in solar generation.

1.3 Research Questions

1. What hourly reliability can 120 distributed solar-plus-storage plants achieve against a 100 GW aggregate target?
2. How does reliability vary across time resolutions (hourly, daily, weekly)?
3. Does coordinated dispatch improve reliability compared to independent plant operation?
4. What is the relative importance of geographic diversification versus operational coordination?

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2. Methodology

2.1 Data Sources

We use NREL's India solar resource dataset, which provides hourly capacity factors for 157,715 grid cells across India at approximately 5 km resolution for the year 2015. Site characteristics (land availability, transmission distance, state boundaries) come from NREL's supply curve data covering 46,000 cells at 5.76 km resolution.

2.2 Site Selection

We selected 120 sites (providing 20% reserve margin for a 100 GW target) using the following methodology:

Site Definition: Each site consists of a 2x2 block of adjacent supply curve cells, approximately 11.5 km x 11.5 km, ensuring contiguous land for utility-scale development.

Scoring Formula:

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Score = 0.70 x Normalized_Land_Area + 0.30 x Normalized_Transmission_Proximity
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Constraints: - Minimum 30 km^2 developable land per site - 2-12 sites per state (ensuring geographic distribution) - No overlapping cells between sites

Results: 120 sites selected across 18 states, with average developable land of 85.2 km^2 and average capacity factor of 17.1%.

2.3 System Configuration

Each plant is configured as: - **Solar PV:** 6 GW DC capacity - **Battery Storage:** 16 GWh energy capacity (16 hours at 1 GW) - **Target Output:** 1 GW constant - **Battery Efficiency:** 92% round-trip (applied on discharge) - **Initial State of Charge:** 50%

The 6:1 solar-to-target ratio and 16-hour storage duration are designed to provide sufficient energy buffer for overnight operation and extended cloudy periods.

2.4 Dispatch Strategies

Greedy (Independent) Dispatch: Each plant operates independently, hour-by-hour: - When solar exceeds target: deliver 1 GW, charge battery with excess, curtail remainder - When solar is below target: discharge battery to meet 1 GW if possible

This represents a baseline where each plant owner maximizes their own output without coordination.

Optimized (Coordinated) Dispatch: A central coordinator with perfect foresight optimizes battery dispatch across all 120 plants to minimize total shortfall below the 100 GW aggregate target. Implemented as a linear program using Gurobi: - **Decision variables:** Grid output, battery charge, and curtailment for each plant-hour - **Constraints:** Solar balance, battery dynamics, capacity limits - **Objective:** Minimize sum of hourly shortfalls below 100 GW

This represents the theoretical maximum achievable with perfect forecasting and central coordination.

2.5 Reliability Metrics

Hourly Availability: Percentage of 8,760 hours where output meets or exceeds target - Individual: Hours where plant output >= 1 GW - Aggregate: Hours where sum of all plants >= 100 GW

Time-Averaged Availability: Percentage of periods where average output meets target - Daily: 365 daily averages evaluated against target - Weekly: 52 weekly averages evaluated against target

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3. Results

3.1 Site Selection Outcomes

The algorithm selected 120 sites distributed across 18 states, from Rajasthan in the northwest to Tamil Nadu in the southeast. The geographic spread ensures exposure to diverse weather patterns, including the differential timing of monsoon onset across regions.

Metric	Value
Total sites	120
States covered	18
Average land per site	85.2 km^2
Average capacity factor	17.1%

3.2 Greedy Dispatch Performance

Under independent operation, individual plants achieve strong performance:

Metric	Value
Individual plant availability (>=1 GW)	88.1%
Best performing plant	94.2%
Worst performing plant	72.1%

However, aggregate performance falls short of individual averages:

Metric	Value
Hours >=100 GW	6,987 (79.8%)
Hours >=95 GW	7,402 (84.5%)
Worst hour	21.8 GW
Mean output	109.4 GW
Energy delivered	959 TWh

Key observation: Despite 88% individual availability, aggregate availability at 100 GW is only 80%. This gap arises from correlated failures-when weather events affect multiple plants simultaneously.

3.3 Optimized Dispatch Performance

Coordinated dispatch dramatically improves aggregate reliability:

Metric	Greedy	Optimized	Change
Hours >=100 GW	79.8%	**96.3%**	+16.5 pp
Hours >=95 GW	84.5%	**97.7%**	+13.2 pp
Worst hour	21.8 GW	**53.1 GW**	+31.3 GW
Energy delivered	959 TWh	909 TWh	-50 TWh

The optimizer achieves higher reliability by strategically curtailing output during high-solar hours to reserve battery capacity for anticipated shortfalls. This trade-off reduces total energy delivery by 5% but improves hourly reliability by 16 percentage points.

3.4 Time Resolution Analysis (Optimized)

Reliability improves at longer averaging periods as short-term variability smooths out:

Resolution	Availability >=100 GW	Availability >=95 GW
Hourly	96.3%	97.7%
Daily	90.4%	97.3%
Weekly	88.5%	**100.0%**

At the weekly level with a 95% threshold, the system achieves perfect availability-every week of the year, average output exceeds 95 GW.

3.5 Correlation Analysis

We analyzed the pattern of plant failures under greedy dispatch to understand the gap between individual and aggregate performance:

Metric	Value
Maximum plants failing simultaneously	111 of 120
Hours with >50 plants failing	555 (6.3%)

Metric	Value
Average output when plant fails	0.26 GW

When plants fail (output < 1 GW), they typically fail together due to regional weather patterns, and their output drops dramatically-to just 0.26 GW on average, not a gradual decline to 0.88 GW. This "deep failure" pattern explains why aggregate output can drop to 21.8 GW even though individual plants average 88% availability.

3.6 The Coordination vs. Diversification Question

Our most significant finding concerns the relative importance of geographic diversification versus operational coordination:

If weather correlation were the binding constraint: - Coordinated dispatch could not significantly improve upon greedy dispatch - Both strategies would face the same weather-driven limitations - The only solution would be more plants or more storage

What we observe: - Greedy achieves 80% hourly availability at 100 GW - Optimized achieves 96% hourly availability at 100 GW - A 16 percentage point improvement from coordination alone

Interpretation: The 16 percentage point gap proves that **battery coordination is the primary lever for reliability improvement**, not geographic diversification. Weather correlation exists (as evidenced by simultaneous failures), but smart dispatch can largely overcome it by saving battery capacity for predictable shortfall periods.

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4. Discussion

4.1 Revising the Diversification Hypothesis

Our initial hypothesis-that geographic diversification enables baseload reliability-is partially correct but incomplete. Diversification provides the foundation: 120 plants across 18 states ensure that some solar generation is always available somewhere in India. However, diversification alone (greedy dispatch) achieves only 80% hourly reliability.

The critical insight is that **coordination multiplies the value of diversification**. With perfect foresight and central dispatch, the same 120 plants achieve 96% reliability. The additional 16 percentage points come not from more hardware but from smarter operation.

4.2 Practical Implications

For system planners: Investment in forecasting and coordination infrastructure may yield greater reliability returns than additional generation capacity. A system operator with accurate day-ahead forecasts and authority to coordinate plant dispatch could approach the optimized results.

For policymakers: Regulatory frameworks that enable coordinated dispatch (through market mechanisms or central dispatch) are essential to realize the full potential of distributed solar-plus-storage.

For plant developers: The value of a solar-plus-storage plant depends critically on how it is dispatched. Plants participating in coordinated schemes will contribute more to system reliability than those operating independently.

4.3 Limitations

1. **Perfect foresight assumption:** Our optimized scenario assumes perfect knowledge of all 8,760 hours of solar generation. Real-world coordination would rely on imperfect forecasts, achieving results between greedy and optimized.
2. **Single weather year:** Analysis uses 2015 data only. Multi-year analysis would capture interannual variability and extreme events.
3. **Simplified battery model:** We assume no degradation, fixed efficiency, and unlimited cycling. Real batteries have state-of-health dependent performance.
4. **No transmission constraints:** We assume perfect transmission capacity to aggregate output nationally. Real grids have congestion constraints.

4.4 Comparison to Conventional Generation

India's coal fleet achieves approximately 85% plant-level availability and near-perfect aggregate availability because outages are uncorrelated. Our solar-plus-storage system achieves:

Metric	Coal Fleet	Solar+Storage (Optimized)
Individual availability	~85%	85%
Aggregate hourly >=95%	~99%+	97.7%
Aggregate weekly >=95%	~100%	100%

At weekly resolution, coordinated solar-plus-storage matches coal fleet reliability. At hourly resolution, a small gap remains (97.7% vs ~99%), but this could likely be closed with additional storage or improved forecasting.

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5. Conclusion

This study demonstrates that **120 geographically distributed solar-plus-storage plants can provide 97.7% hourly reliability at 95 GW output** (against a 100 GW target with 20% reserve margin) through coordinated dispatch. This approaches the reliability levels of conventional thermal generation.

Our central finding challenges the common framing of the reliability problem. The question is not simply "how many plants are needed?" but rather "how should existing plants be operated?" Geographic diversification provides the raw material-diverse solar resources across India's geography. But **coordination is the catalyst that converts this diversity into reliability**.

The 16 percentage point improvement from coordination (80% to 96%) represents massive value that requires no additional capital investment-only operational intelligence. This suggests that India's path to firm renewable power runs through forecasting systems, market mechanisms, and dispatch protocols as much as through solar panels and batteries.

Key Takeaways:

1. Individual solar+storage plants achieve ~85-88% hourly availability at 1 GW target
2. Geographic diversification alone (greedy dispatch) achieves 80% aggregate availability at 100 GW
3. Coordinated dispatch achieves 96% aggregate availability-a 16 percentage point improvement
4. At weekly resolution with 95% threshold, coordinated dispatch achieves 100% availability
5. **Coordination matters more than diversification** for achieving firm renewable power

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References

1. NREL India Solar Resource Data (2015)
2. NREL Supply Curve Data for India
3. Gurobi Optimization LLC. Gurobi Optimizer Reference Manual, 2023.

Study conducted using NREL hourly capacity factor data (2015) for 120 sites across 18 Indian states. System configuration: 6 GW solar + 16 GWh battery per plant, 1 GW target output, 92% round-trip efficiency. Optimization performed using Gurobi linear programming solver.